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Soil Temperatures in Alaska's Arctic National Parks, 2011-2015, and Implications for Permafrost Stability

Natural Resource Report NPS/ARCN/NRR—2016/1109

ON THE COVER
The Imelyak climate monitoring station in Noatak National Preserve, 20 July 2015. This windswept mountain top location has a thin, rocky soil sparse vegetation of dwarf alpine shrubs and herbs. The mean annual air and soil temperatures in the past two years were about -5° C and -4° C, respectively. NPS photo by Ken Hill.

Soil Temperatures in Alaska's Arctic National Parks, 2011-2015, and Implications for Permafrost Stability

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Abstract

Monitoring at 21 stations in the Arctic Inventory and Monitoring Network (ARCN) of National Parks in Alaska shows that mean annual air and soil temperatures increased 3° to 4° C during the period from 2011 to 2015. The significance of this increase is uncertain, however. Long-term air temperature records at Bettles (in the interior near the southeastern corner of ARCN) show that the current warm period resembles several others that have occurred since 1976, with air temperatures about 1.5 ° C above the long-term normal (1981-2010). In contrast, air temperature records at Kotzebue (on the coast near the western part of ARCN) show that mean annual temperatures in the past two years have been about 3° C above the long-term normal and represent the highest mean annual temperatures recorded over the entire 80-year period of record. If these warm temperatures were to persist, they would fulfill the mean annual temperature increase that has been predicted to occur by 2046-2065, based on global circulation models (the 2013 IPCC report, van Oldenborgh 2013). The next few years will be crucial to determining if the present warm spell is just a temporary cyclical phenomenon or a significant warming trend.

Permafrost stability is controlled by both the regional climate and the local soil-site conditions. The soil-site conditions result in local permafrost temperatures that range from about 0° C to 5° C above mean annual air temperatures (MAAT). The regional climate is cold enough over most of ARCN to keep permafrost frozen in spite of the recent warming. However, if current warm conditions persist, permafrost will start to degrade in the portions of ARCN with the warmest MAATs combined with the warmest local soil-site conditions: places with relatively deep snow and tall shrub or forest vegetation in the low-elevation, southern portions of Kobuk Valley National Park, Noatak National Preserve (the extreme southwestern part), and Gates of the Arctic National Park and Preserve. A significant cold period involving a drop in MAAT of 3° C to 5° C would be required to bring ground temperatures back to long-term normals and prevent initiation permafrost thaw in these areas.

Acknowledgments

Thanks to Pam Sousanes and Ken Hill for installing and maintaining the ARCN climate stations, managing the climate station data, and for helpful discussions. Thanks also to Vladimir Romanovsky of the University of Alaska Geophysical Institute for providing long-term borehole temperature data. Thanks to Ken Hill and Jon O'Donnell for review comments.

List of Terms and Acronyms

Active layer. Ground above *permafrost* that thaws each summer and refreezes each winter.

ARCN. The NPS Arctic Inventory and Monitoring Network.

BELA. Bering Land Bridge National Preserve.

CAKR. Cape Krusenstern National Monument.

Ecotype. A composite vegetation-soil class used in the ARCN-wide map by Jorgenson et al. (2009).

GAAR. Gates of the Arctic National Park and Preserve.

KOVA. Kobuk Valley National Park.

MAAT. Mean annual air temperature.

MAST. Mean annual soil temperature.

NOAT. Noatak National Preserve.

NPS. National Park Service

Permafrost. Ground that remains below 0° C for two or more consecutive years. In ARCN most permafrost has been frozen for thousands of years and is many meters thick.

RCP 4.5. Representative Concentration Pathway 4.5. A greenhouse gas concentration scenario, used in global climate models, that assumes greenhouse gasses will continue to rise at approximately current rates and then level off after the year 2050.

TDD. Thaw degree-days. Sum of daily positive temperatures (in degrees C) through the year.

Thermal offset. The decrease in mean annual ground temperature that occurs in the *active layer*, between the ground surface and the top of the permafrost.

Introduction

Permafrost underlies nearly all of the National Park Service (NPS) Arctic Inventory and Monitoring Network (ARCN; Fig. 1, Jorgenson et al. 2008). Permafrost is maintained by cold climatic conditions, and it is vulnerable to thaw by disturbance or climate change. Permafrost thaw resulting from climate change, and consequent changes to landforms and ecosystems, have been documented in Alaska (Jorgenson et al. 2001, 2006, Osterkamp 2005). Because of its importance to arctic ecosystems and its vulnerability to change, permafrost was chosen as a monitoring vital sign in ARCN (Lawler et al. 2009).

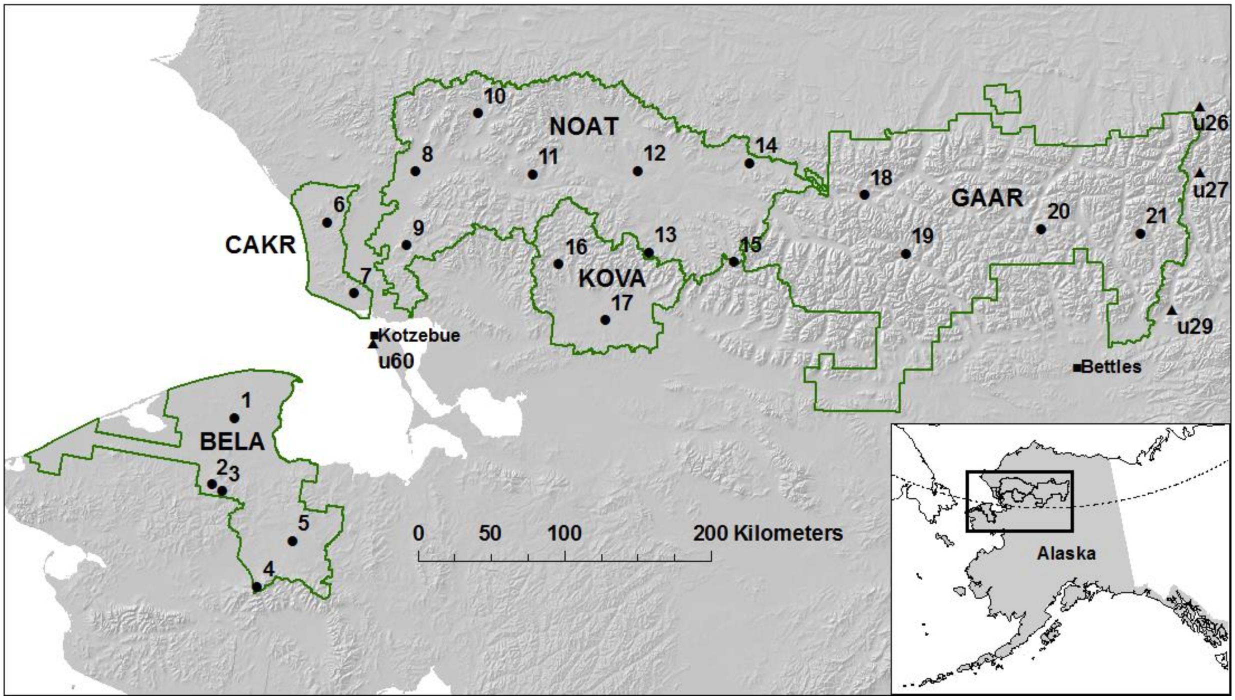


Figure 1. Location of the Arctic Network climate monitoring stations. Stations are identified in Tables 1 and 2. The National Park unit abbreviations are Bering Land Bridge National Preserve (BELA), Cape Krusenstern National Monument (CAKR), Gates of the Arctic National Park and Preserve (GAAR), Kobuk Valley National Park (KOVA), and Noatak National Preserve (NOAT).

The ARCN permafrost monitoring program includes both monitoring of landforms resulting from permafrost thaw (Swanson 2013, 2014) and monitoring of ground temperatures, the subject of the present report. Monitoring of ground temperatures is an important complement to landform monitoring, because it allows us to relate observed landscape changes to climate. Ground temperatures are monitored at a network of climate monitoring stations (Fig. 1, Table 1) and deep boreholes (Fig. 1, Table 2). To facilitate data transmission to satellites, the climate monitoring stations recently installed by NPS (Hill and Sousanes, 2015a, 2015b; type "RAWS NPS" in Table 1) are dominantly on hill or mountain tops, with sparse vegetation and shallow depth to bedrock. The older stations originally installed for fire management ("RAWS" in Table 1) and the NRCS

Table 1. ARCN Climate Monitoring Stations

ID	NPS Unit	Name	Type[1]	Latitude, decimal degrees	Longitude, decimal degrees	Elevation, m	Soil Temperature Install Date	Ecotype[2]
1	BELA	Devil Mountain	RAWS NPS	66.276	-164.531	87	18 Aug 2011	Upland sedge-dryas meadow
2	BELA	Serpentine Hot Springs	RAWS NPS	65.852	-164.708	158	17 Aug 2011	Upland birch-ericaceous low shrub
3	BELA	Midnight Mountain	RAWS NPS	65.820	-164.543	691	6 Aug 2013	Alpine acidic barrens
4	BELA	Ella Creek	RAWS NPS	65.275	-163.820	707	18 Sept 2012	Alpine barrens
5	BELA	HooDoo Hills RAWS	RAWS	65.586	-163.408	144	3 Sept 2014	Upland dwarf birch-tussock shrub
6	CAKR	Tahinichok	RAWS NPS	67.550	-163.567	294	10 July 2011	Alpine dryas dwarf shrub
7	CAKR	Mt. Noak	RAWS NPS	67.141	-162.995	247	11 July 2011	Upland sedge-dryas meadow
8	NOAT	Kelly SNOTEL	SNOTEL	67.933	-162.283	94	7 Aug 2012	Upland white spruce-ericaceous forest
9	NOAT	Asik	RAWS NPS	67.475	-162.266	405	13 July 2012	Alpine alkaline dryas dwarf shrub
10	NOAT	Kugururok	RAWS NPS	68.333	-161.376	311	18 July 2014	Upland birch-ericaceous-willow low shrub
11	NOAT	Sisiak	RAWS NPS	67.995	-160.396	556	13 July 2011	Alpine dryas dwarf shrub
12	NOAT	Noatak RAWS	RAWS	68.071	-158.704	91	25 July 2014	Upland dwarf birch-tussock shrub
13	NOAT	Kaluich Creek	RAWS NPS	67.573	-158.432	735	20 July 2012	Alpine acidic barrens
14	NOAT	Howard Pass	RAWS NPS	68.156	-156.896	628	7 July 2011	Alpine acidic barrens
15	NOAT	Imelyak	RAWS NPS	67.545	-157.077	1103	6 July 2011	Alpine acidic barrens
16	KOVA	Salmon River	RAWS NPS	67.460	-159.841	385	8 July 2011	Upland birch-ericaceous low shrub
17	KOVA	Kavet Creek RAWS	RAWS	67.139	-159.044	22	25 July 2014	Upland birch-ericaceous low shrub
18	GAAR	Killik Pass	RAWS NPS	67.984	-155.013	1329	8 Aug 2012	Alpine dryas dwarf shrub
19	GAAR	Ram Creek	RAWS NPS	67.624	-154.345	1250	7 Aug 2012	Alpine dryas dwarf shrub
20	GAAR	Pamichtuk Lake	RAWS NPS	67.766	-152.165	956	6 Aug 2012	Alpine ericaceous-dryas dwarf shrub
21	GAAR	Chimney Lake	RAWS NPS	67.714	-150.585	1128	7 Aug 2012	Alpine dryas dwarf shrub

[1]RAWS NPS – Remote automated weather station established by NPS since 2011; RAWS – weather station established by BLM for fire science purposes in the 1990s. SNOTEL – USDA-NRCS snow telemetry monitoring site.

[2]By the classification used in the ARCN-wide map by Jorgenson et al. (2009)

Table 2. Deep Borehole Locations in the ARCN Vicinity[1]

Site	Name	Latitude, Decimal Degrees	Longitude, Decimal Degrees	Drill Date	Ecotype[2]
u27	Chandalar Shelf	68.069068	-149.580424	5/3/1985	Upland dwarf birch-tussock shrub
u29	Coldfoot	67.237268	-150.161443	12/3/1983	Upland dwarf birch-tussock shrub
u26	Galbraith Lake	68.477413	-149.502416	5/2/1985	Alpine wet sedge meadow
u60	Kotzebue	66.851820	-162.604330	8/16/1982	Upland dwarf birch-tussock shrub

[1]Stations are part of the statewide network described by Osterkamp (2003)

[2]By the classification used in the ARCN-wide map by Jorgenson et al. (2009)

SNOTEL site are on fine-grained soils in lowlands. Full soil and site descriptions are available for six of the stations (Appendix).

Ground surface temperatures closely follow air temperatures, except when snow is present. Ground surface temperatures under snow are warmer than air temperatures through most of the winter due to the insulating effect of the snow, and thus the mean annual ground surface temperature at a particular location is usually higher than the mean annual air temperature (MAAT). The amplitude of the annual wave in temperature is gradually damped with depth in the soil (Fig. 2). MAAT and mean annual soil temperatures (MAST) in the active layer (the portion that thaws each summer, Fig. 2) are closely related to permafrost temperatures, and they are particularly useful when measurements deep enough to be in actual permafrost are not available.

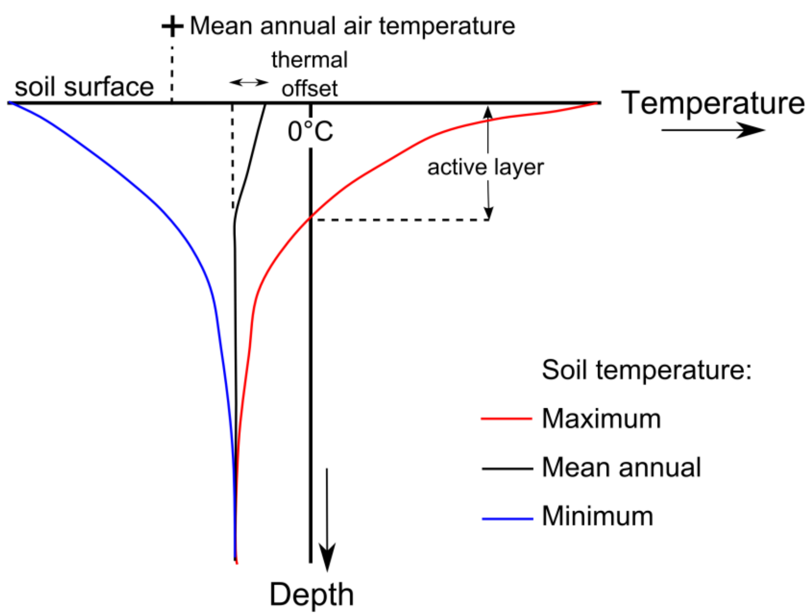


Figure 2. Diagram of annual maximum, minimum, and mean ground temperatures with depth The active layer is the portion near the surface that warms above 0° C in the summer. Thermal offset (Burn and Smith 1988) is the decline in mean annual temperature with depth in the active layer that is observed in many soils. The mean annual air temperature (MAAT) is usually lower than the mean annual soil temperature (MAST).

Mean annual temperatures in permafrost just below the active layer are usually 0° C to 5° C warmer than MAAT, depending on snow and active-layer thermal properties. As a result, permafrost is present nearly everywhere on the landscape (except under deep water bodies) when the MAAT is below -5° C, and it generally occupies progressively less of the land area at higher MAATs, becoming nearly absent where MAAT is above 0° C (Jorgenson et al. 2008). Long-term MAATs in ARCN range from -3 to -12° C, with most of the land area between -5 and -10° C (Fig. 3, Table 3).

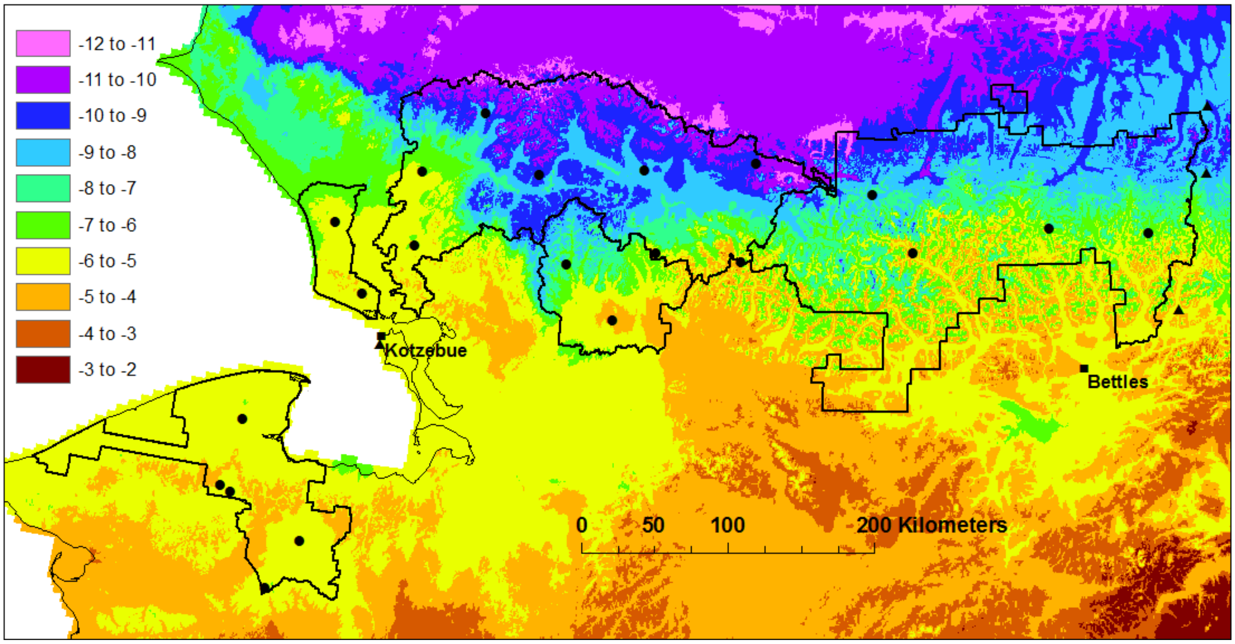


Figure 3. Mean annual air temperatures in ARCN. Model data from PRISM Climate Group (2009). Circles and triangles mark monitoring locations identified in Fig. 1.

Table 3. Area of ARCN occupied by various ranges in MAAT.

MAAT, ° C[1]	Proportion of ARCN, %
-3 to -4	<1
-4 to -5	8
-5 to -6	29
-6 to -7	13
-7 to -8	12
-8 to -9	17
-9 to -10	14
-10 to -11	5
-11 to -12	1

[1]Air temperatures modeled by PRISM Climate Group (2009; Fig. 3). Permafrost is typically continuous where MAAT is below -5° C.

The thickness of the active layer can change if mean annual temperatures increase (i.e. if the whole "funnel" enclosed by the maximum and minimum temperatures in Fig. 2 shift to the right), or if summer warmth alone increases. The summer warmth available for thaw of the active layer is often quantified using the seasonal sum of thaw degree-days (TDD; U.S. Army Corps of Engineers 1950). Seasonal sum of thaw degree-days (TDD) is a useful predictor of year-to-year variations in the depth of summer thaw (Hinkel and Nicholas 1995, Nelson et al 1997).

According to global circulation models based on the RCP 4.5 scenario, MAATs in ARCN are predicted to increase about 1° C (in the east) to 2° C (in the west) by the year 2035, about 3° C by 2065, and 4-5° C by 2100 (van Oldenborgh 2013).

Methods

Temperature

We measured soil and air temperatures at 21 monitoring stations in ARCN (Fig. 1). These stations include 17 remote automated weather stations (RAWS) installed by NPS since 2011; 3 RAWS maintained jointly by the Bureau of Land Management (BLM) and NPS that have been operating since the 1990s and were outfitted with soil temperature sensors in 2014; and one snow telemetry (SNOTEL) site maintained by the USDA-NRCS and outfitted with soil temperature sensors in 2012. For station technical specifications, see Hill and Sousanes (2015a,b). Soil sensors were at depths of 10, 20, 50, and, at 4 stations only, 75 cm. Snow depth was measured hourly with a sonic ranging sensor. Mean hourly temperatures were computed from readings made every minute. These means were transmitted hourly and also stored onsite in the data loggers at the stations; the stored data were collected annually and used to correct the telemetry data (at RAWS NPS stations only). The RAWS data are stored by the Western Regional Climate Center (http://www.raws.dri.edu/wraws/akF.html) and the Applied Climate Information System (ACIS, http://xmacis.rcc-acis.org/). The SNOTEL data are available from the USDA NRCS National Water and Climate Center (http://www.wcc.nrcs.usda.gov/reportGenerator/).

MAATs and MASTs were computed from the hourly data as follows. Daily means were computed from the hourly mean data with an 80% threshold for missing data, i.e., a day was considered "missing" if less than 80% of the hourly readings were available. Monthly mean temperatures were computed from these daily means, again with an 80% threshold for missing data. MAATs, and MASTs at each available sensor depth in the soil, were computed monthly for the following 12 months (Fig. 4). Daily medians were computed from hourly snow data, and these daily values were used to compute a mean snow depth for the period November-March, the period when it has the greatest warming effect on soil temperatures.

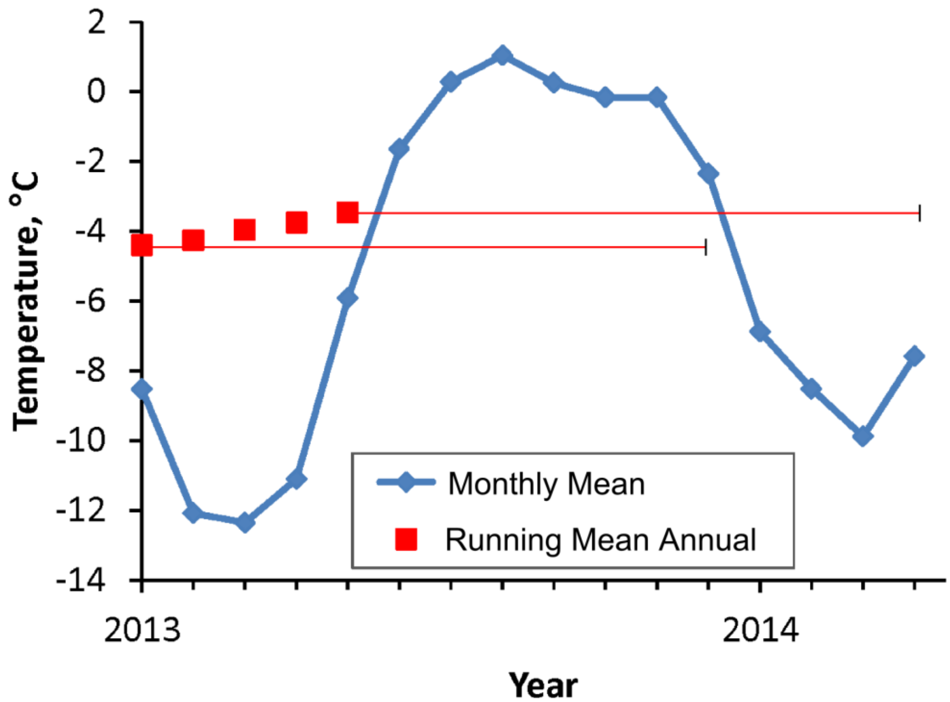


Figure 4. Computation of mean annual temperatures. Running mean annual air temperatures (MAAT) and soil temperatures (MAST) were computed monthly for the following year. This example shows 50 cm soil temperatures at Devil Mountain. Six annual means were computed for this period of 16 months. The horizontal red lines show the interval over which the annual mean was computed for two of the means. Running annual means make better use of discontinuous data than fixed-interval annual means (e.g. calendar years).

Additional historical perspective was supplied by a 20-year record of deep borehole temperatures at four monitoring sites near ARCN (Fig 1 and Table 2), originally established by Tom Osterkamp of the University of Alaska Fairbanks (UAF) and re-measured over the years by him and UAF professor Vladimir Romanovsky (Osterkamp 2003, 2005, 2007; Osterkamp and Romanovsky 1996; Romanovsky et al. 2015). I chose a common depth of 26 m for comparison of the 4 boreholes. This depth is just below the typical depth of perceptible penetration of annual temperature waves, which is about 20 m (Osterkamp 2005), and it is the shallowest depth with measurements available for all 4 boreholes and all sample years.

Soil and Site Descriptions

I described the soil at six stations in 2015 based on a small pit (approximately 0.5 m diameter) using standard USDA methods (Soil Survey Division Staff 1993, Schoeneberger et al. 1998). I classified the soils with the Keys to Soil Taxonomy (Soil Survey Staff 2014). I also made ocular estimates of plant species cover for the plant community occupied by the station. These descriptions are provided in the Appendix. Our plan is to complete descriptions for the remaining stations over the next few years. Each station was also assigned to an ecotype (composite vegetation-soil class) by the system used in the ARCN-wide map by Jorgenson et al. (2009; Table 1). For the 15 stations not visited by the author in 2015, ecotypes were assigned tentatively based on photographs.

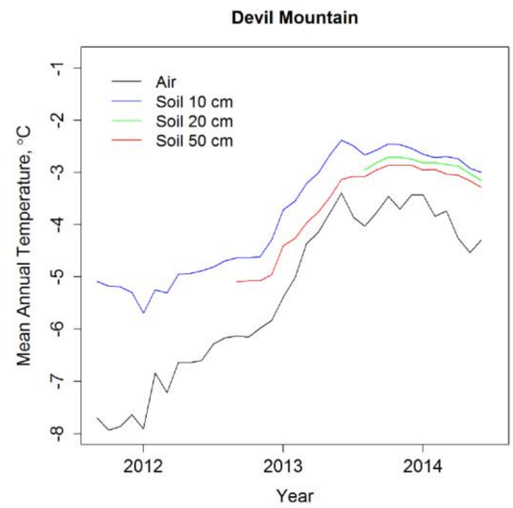
Results

Mean Annual Air and Soil Temperatures

All of our climate monitoring stations showed an increase in MAAT during 2012 and 2013 (Figs. 5-8). At locations where our records began early enough to cover all of 2012, the change in MAAT 2012-2014 was +3° C to +4° C. Where soil temperatures are available for all or part of the transition period, the MAST increased in concert with the MAAT. Warming began with a jump in MAAT and MAST for the 12-month period 2/2012-1/2013 and leveled off starting in the 12-month period 4/2013-3/2014. The apparently smaller increases (+2° C) at stations that began observations in the summer of 2012 or later (e.g. all the GAAR stations) do not necessarily indicate less warming there, because those records do not extend back far enough to capture the entire transition period beginning in 2/2012.

A long-term climate perspective for our area is provided by the time series of MAAT at Bettles and Kotzebue (Figs. 9-10). Both records show repeated fluctuations with a range of about 4° C in time periods of less than 5 years. The interval covered by our soil temperature records (starting in 2011) was a time of increasing air temperatures at both stations from a relative low in 2012 to a high in 2014. At Bettles both the low (-6.8° C for 1/2012-12/2012) and the following high (-3.1° C in 8/2014-7/2015) resemble previous cycles that have occurred since 1976, when the climate over most of Alaska switched abruptly to a warmer regime that has persisted since (Hartmann and Wendler 2005). The 2014-15 MAAT at Bettles was not unprecedented: it was exceeded by peaks in 1976-77, 1981, 1993-94, and 1997-98, and it was only 1.6° C above the 1981-2010 normal of -4.7° C (NOAA 2015). At Kotzebue the 1/2012-12/2012 low of -7.1° C was comparable to previous lows in the post-1976 era, but the subsequent high of -2.0° C for 1/2012-12/2014 was the highest MAAT ever recorded, and exceeded previous highs of -2.6° C in 2002-2005 and -3.3° C in 1978-79; it was nearly 3° C above the 1981-2010 normal of -5.1° C (NOAA 2015) There was a slight decline of MAAT in 2015 at Kotzebue to about -2.5° C. If current warm conditions at Kotzebue persist, they would represent an increase equal to what was predicted to occur by mid-century using global circulation models (van Oldenborgh 2013).

Based on the Seasonal Kendall trend test, the long-term trend for MAAT at Bettles has been flat in the 40 years since the 1976 climatic shift (Table 4 and Wendler et al. 2012). If data prior to the 1976 shift are included in the trend analysis, a significant increase of about +2.5° C per century over the past 50 or 60 years is detected. Visual inspection of Fig. 10 suggests an upward trend in MAAT in Kotzebue in recent decades, but tests of trend for the post-1976 era by the Seasonal Kendall method are somewhat ambiguous (Table 4). Trends are insignificant for the most recent 20- and 40-year intervals due to the warm events around 1980 and 2004, i.e. near the beginning of these intervals. However, a significant cold spell (e.g. a drop in MAAT of about 5° C) must occur in the next few years or the post-1976 increasing trend will become highly significant. Trend is already highly significant for time intervals that extend back prior to the 1976 climatic warming event (Table 4). The rate of increase over the past 50 or 60 years at Kotzebue is about +3° C per century.



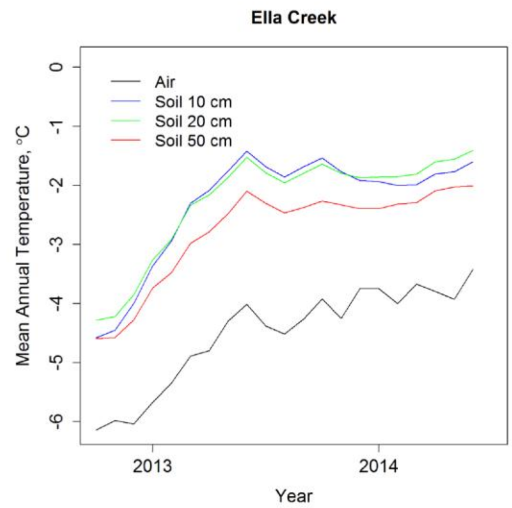
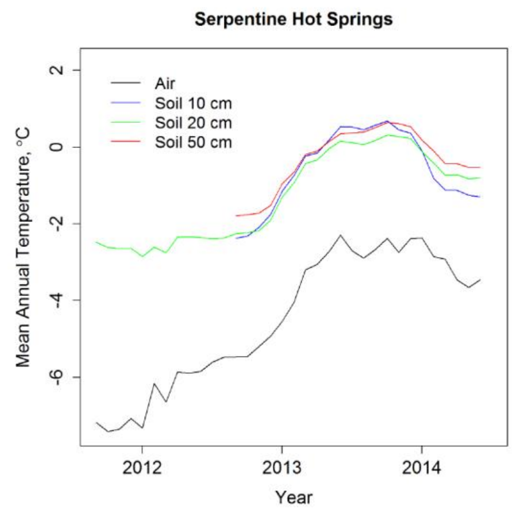
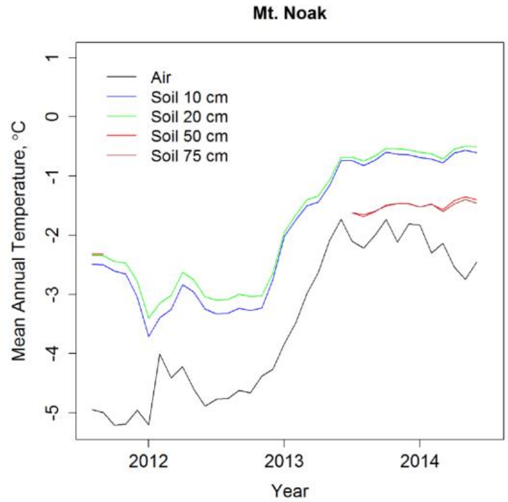
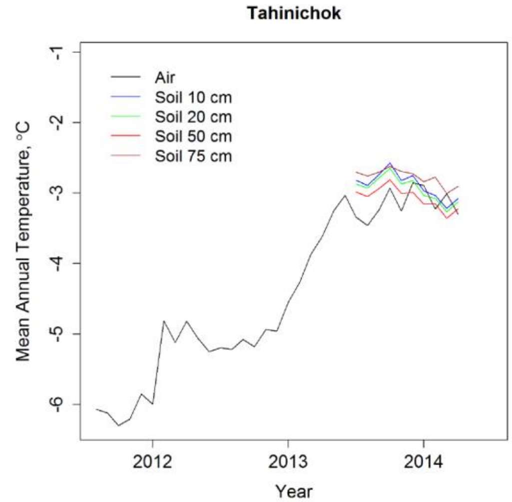


Figure 5. Mean annual air and soil temperatures at the climate monitoring stations in BELA. Here and in Figs. 6 through 10, these are running mean annual temperatures, computed monthly for the following 12 months. Thus the mean plotted at year "2012" is Jan-Dec 2012; the mean plotted at 2012.5 is July 2012-June 2013, etc.







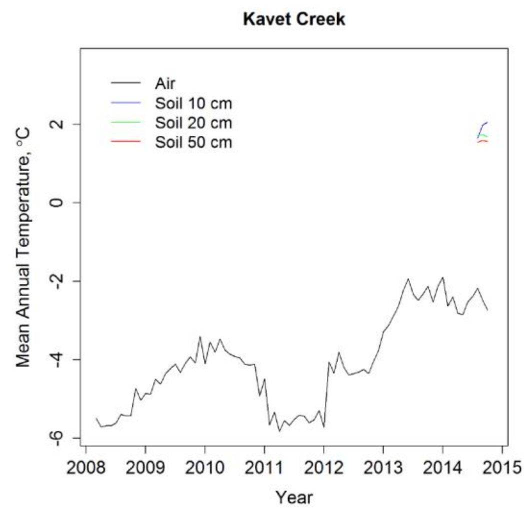


Figure 6. Mean annual air and soil temperatures at the climate monitoring stations in CAKR and KOVA.

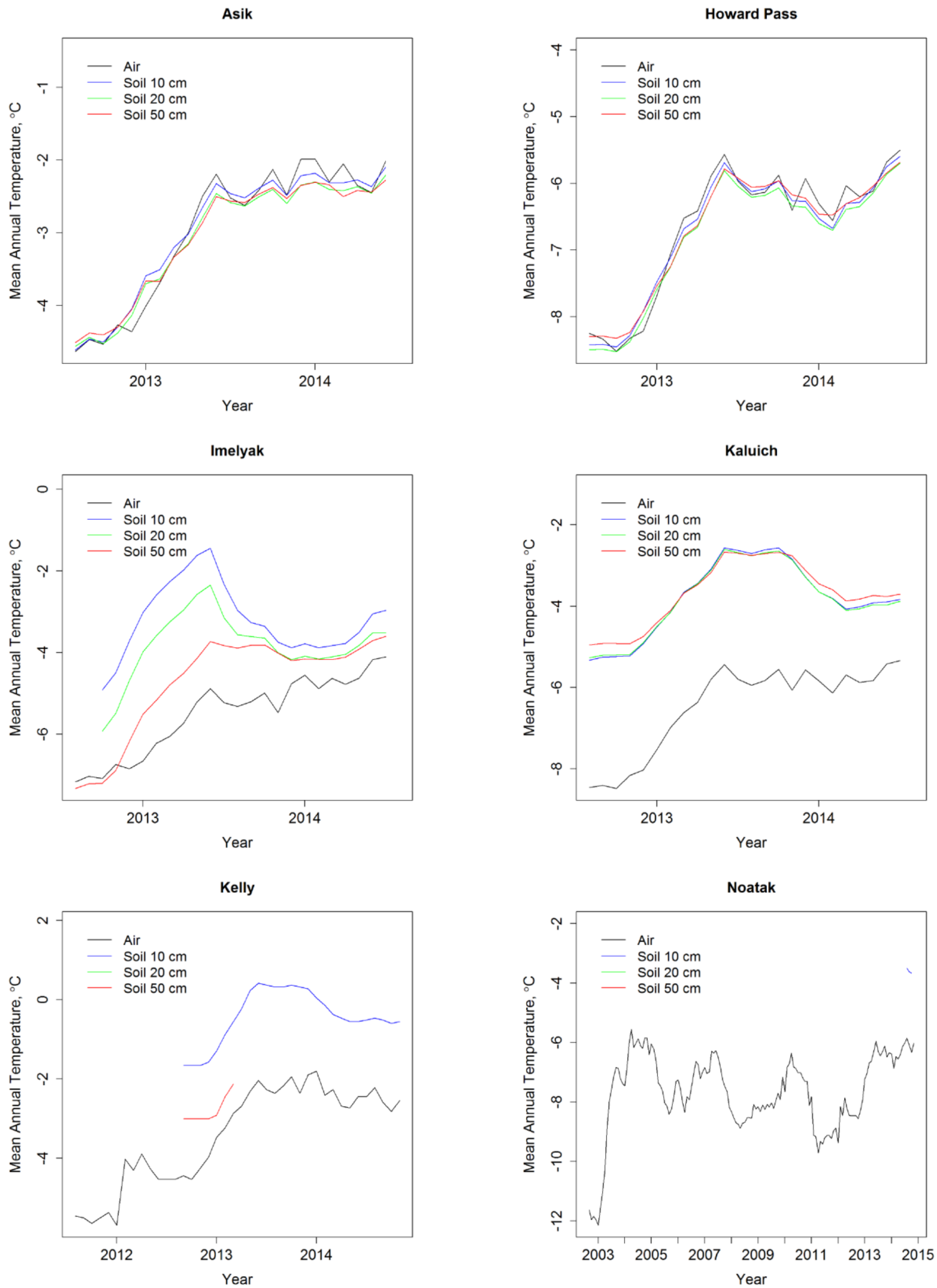


Figure 7. Mean annual air and soil temperatures at the climate monitoring stations in NOAT.

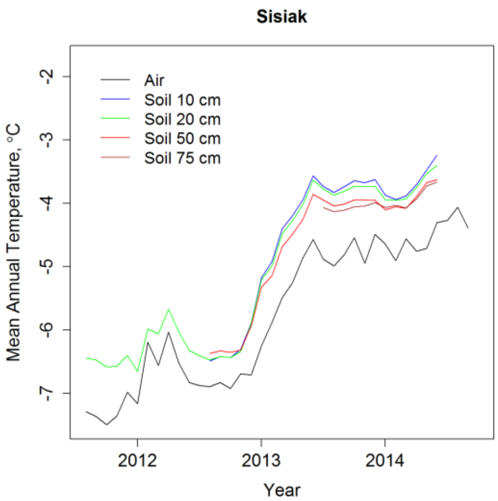
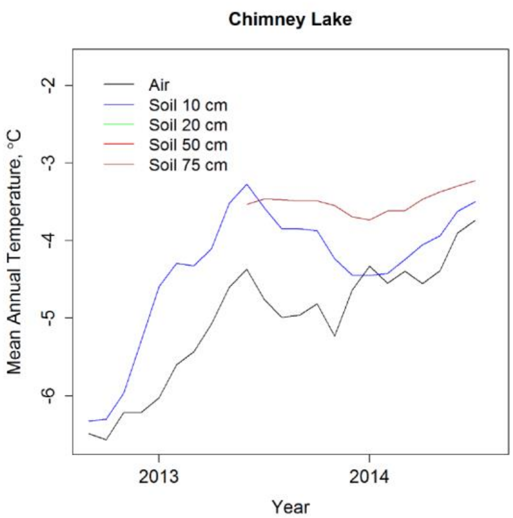


Figure 7 (continued). Mean annual air and soil temperatures at the climate monitoring stations in NOAT.



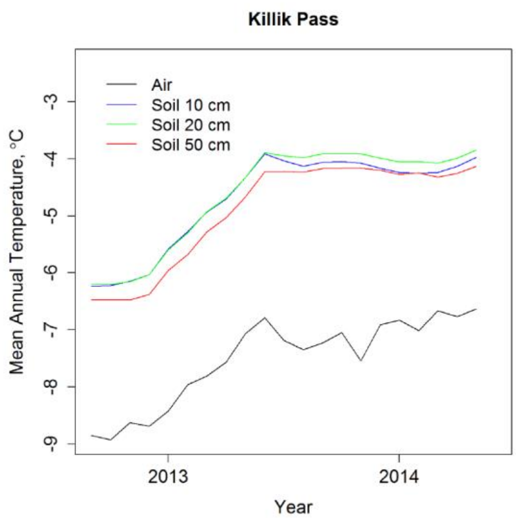
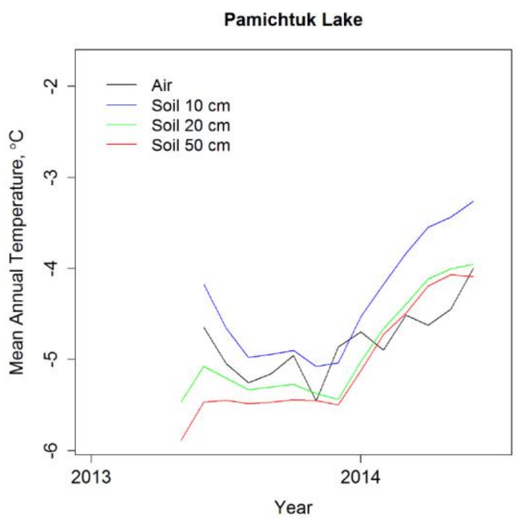


Figure 8. Mean annual air and soil temperatures at the climate monitoring stations in GAAR.



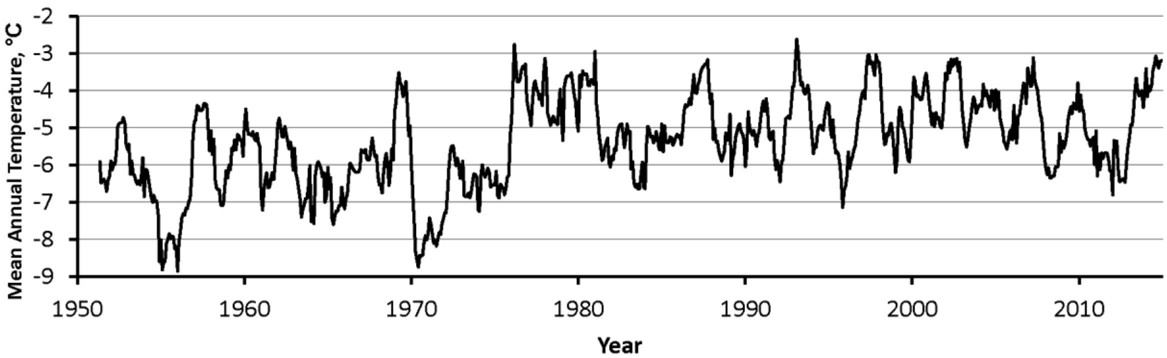


Figure 9. Mean annual air temperature at Bettles, Alaska.

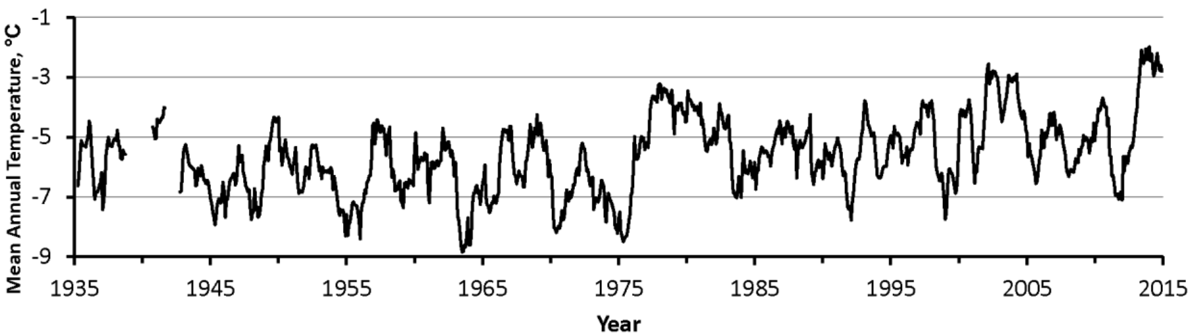


Figure 10. Mean annual air temperature at Kotzebue, Alaska.

Table 4. Test of Trend in Monthly Mean Temperatures at Bettles and Kotzebue by the Seasonal Kendall Method[1]

	Bettles		Kotzebue	
Time Interval	**Slope °C year^{-1}**	**Adjusted Mann-Kendall probability**	**Slope °C year^{-1}**	**Adjusted Mann-Kendall probability**
10 years (2005-2015)	-0.003	0.960	0.222	0.060
20 years (1995-2015)	0.000	0.987	0.056	0.206
30 years (1985-2015)	-0.010	0.596	0.037	0.084
40 years (1975-2015)	0.000	0.942	0.019	0.218
50 years (1965-2015)	**0.023**	**0.011**	**0.032**	**0.008**
60 years (1955-2015)	**0.027**	**0.000**	**0.032**	**0.000**
70 years (1945-2015)	ND	ND	**0.029**	**0.000**
80 years (1935-2015)	ND	ND	**0.020**	**0.000**

[1]Non-parametric Mann-Kendall trend test, extended for use in data sets with annual cycles by Hirsch et al. (1982) and Hirsch and Slack (1984), implemented in R by Marchetto (2015). The adjusted Mann-Kendall probability value corrects for the effect of serial autocorrelation. Highly significant (P > 0.05) probabilities are in boldface. ND – No data.

Continued warming since the 1976 climatic shift has been observed on the North Slope and was shown there to be closely linked to the decrease in sea ice (Wendler et al. 2014). Coastal arctic regions in Alaska are predicted to have more warming in the coming century than interior regions (van Oldenborgh 2013). This raises the question of how far inland do the current warmer, coastal (i.e. Kotzebue-like) conditions extend, and where might conditions resemble Bettles instead. Air temperature records from the Kavet Creek and Noatak RAWS extend back further than the NPS stations, but still do not satisfactorily answer this question. At Kavet Creek (Fig. 6), the latest warm spell is warmer than the previous one in 2011, but this was also true at both Kotzebue and Bettles. At the Noatak RAWS (Fig. 6), the current warm spell is similar to the three others that have occurred in the past 10 years, suggesting a more Bettles-like trend, but the length of current warm spell is longer than the previous three. The next few years will be crucial to determining if the present warm spell is just a temporary cyclical phenomenon or part of a significant new warming trend.

Difference between MAAT and MAST

Air and near-surface soil temperatures. MASTs near the surface (10 cm depth: $MAST_{10}$) are generally higher than MAAT, as a result of winter snow insulation and radiative heating of the ground (Figs. 5-8, and Table 5). In ARCN the largest difference between $MAST_{10}$ and MAAT was +4.4° C at the Kavek Creek station in KOVA, although we have just over one year of data there. Snow data are not available at Kavet Creek, but trees and 1-m tall shrubs probably allow accumulation of a thick, low-density taiga-type snowpack with good insulation value (Sturm et al. 1995). The other stations with more than 15 cm of snow in all years were Ella Creek in BELA, Salmon River in KOVA, and Kaluich and Kelly in NOAT (Fig. 11). Salmon River has incomplete temperature data, the other two sites have relatively high $MAST_{10}$-MAAT differences: 2.2° C to 2.7° C. All remaining stations had mean winter snow depths of less than 15 cm in all years (with the exception of Ram Creek in GAAR with 1 year at 25 cm) and $MAST_{10}$-MAAT of -0.1° C to 2.8° C. The two stations with $MAST_{10}$-MAAT near zero (Asik and Howard Pass in NOAT) both had negligible snow covers.

Thermal offset. The mean annual temperature declines with depth in most soils (Table 5; $MAST_{50}$-$MAST_{10}$), an effect known as "thermal offset" (Fig. 2, Burn and Smith 1988). Thermal offset is most pronounced in wet soils, and thus it is not surprising that the thermal offset between 10 cm and 50 cm depth in most of our soils is less than 1° C. The unusual reversed gradient - warming with depth in the active layer - at Serpentine Hot Springs station in BELA may be due to geothermal heating. The other strong reversed gradient (Chimney Lake in GAAR) was obtained from a very short period of record and may not be a persistent feature. Thermal offset typically continues down to the permafrost table, so some additional cooling of MAST - perhaps a few more tenths of a degree - is possible below our deepest observations at 50 or 75 cm.

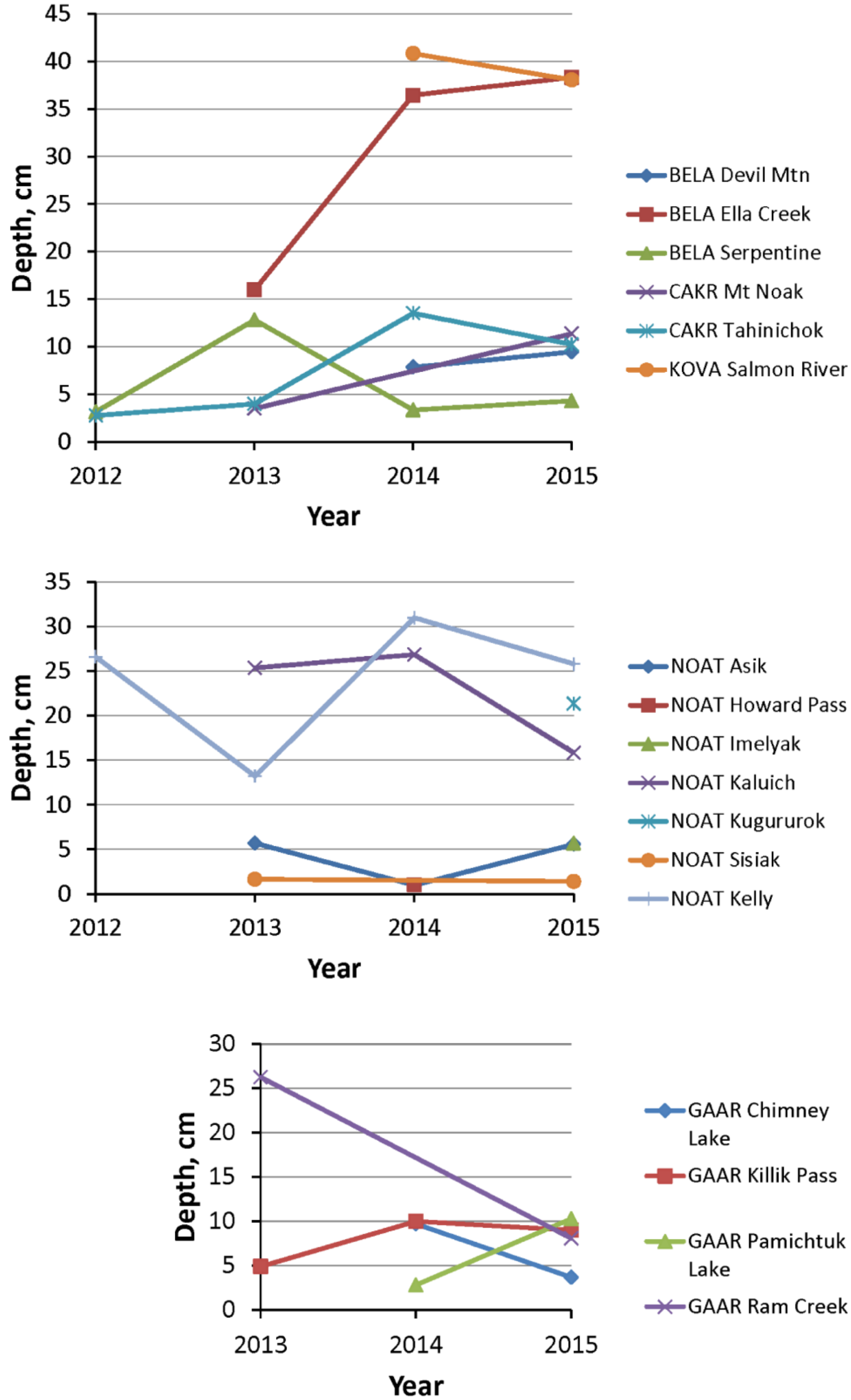


Figure 11. Mean winter (November-March) snow depths at ARCN climate stations. (Preliminary data.)

Table 5. Difference in Mean Annual Temperature between the air, soil at 10 cm depth, and soil at 50 cm depth

NPS Unit	Station	$MAST_{10}$-MAAT, ° C		$MAST_{50}$-$MAST_{10}$, ° C		$MAST_{50}$-MAAT, ° C	
		Mean	N[1]	Mean	N[1]	Mean	N[1]
BELA	Devil Mtn	1.5	34	-0.5	22	0.8	22
BELA	Ella Creek	2.2	21	-0.5	21	1.7	21
BELA	HooDoo Hills	0.8	2	-0.2	2	0.6	2
BELA	Serpentine HS	2.8	22	+0.3	22	3.1	22
CAKR	Mt Noak	1.5	35	-0.7	14	0.9	14
CAKR	Tahinichok	0.3	10	-0.2	10	0.1	10
GAAR	Chimney Lake	0.7	23	+0.4	2	0.7	2
GAAR	Killik Pass	2.8	21	-0.2	21	2.6	21
GAAR	PamichtukLake	0.5	13	-0.6	13	-0.2	13
GAAR	Ram Creek	1.0	1	+0.1	1	1.1	1
KOVA	Kavet Creek	4.4	3	-0.3	3	4.0	3
NOAT	Noatak	2.5	3	ND	0	ND	0
NOAT	Asik	0.0	23	-0.1	23	-0.1	23
NOAT	Howard Pass	-0.1	24	-0.0	24	0.0	24
NOAT	Imelyak[2]	1.0	8	-0.4	8	0.6	8
NOAT	Kaluich	2.7	24	+0.1	24	2.8	24
NOAT	Kelly SNOTEL	2.3	27	-1.5	7	1.0	7
NOAT	Sisiak	0.9	23	-0.2	23	0.7	23

[1]The number of running 12-month means used to compute the mean difference

[2]At Imelyak the summer soil temperatures were anomalously high in the summer of 2013, so the differences here were computed only using data from 11/2013 and later.

Permafrost temperature vs. mean annual air temperature. Owing to thermal offset, our deepest observation is our best estimate of the upper permafrost temperature, and thus our best estimate of the difference between MAAT and upper permafrost temperature is $MAST_{50}$ – MAAT (Table 5). Knowledge of this difference is useful because it allows us to predict permafrost stability from air temperatures, which are more widely available and more readily forecast than ground temperatures. Our data show that for many windswept tundra locations, upper permafrost temperatures are just one degree or less above MAAT, but differences as high as 3° C are possible in tundra environments and 4° or 5° C in forested or tall shrub environments. Two years of soil temperature observations at 1 m depth from 15 sites in Selawik National Wildlife Refuge (Romanovsky and Cable 2014; Selawik NWR is east of Kotzebue, just south of NOAT and KOVA) yielded results generally similar to ours: two tall shrub sites had MAST-$MAST_{100}$ differences of 3.8° C and 4.8° C; various low shrub communities had differences of 2° C to 3° C; and tussock tundra was 0.4 to 2.4° C. One year of data in a white spruce-ericaceous shrub forest had a difference of 2.2° C

The implications are that if MAAT rises above -4° C permafrost will start to degrade on some sites with tall shrub and forest vegetation, and if MAAT rises above -3° C then permafrost will start to degrade on some but not all sites with low shrub, tussock tundra, and Dryas tundra. MAAT would have to reach above 0° C to degrade permafrost on all sites.

Recent ground temperatures, air temperatures, and permafrost stability. The $MAST_{50}$ (or $MAST_{75}$ where available) during the past two years (Table 6) indicates what permafrost temperature would result if the relatively warm conditions of the past two years were to persist. All the NOAT and GAAR stations had relatively cold MAAT (below -4.5° C) and cold $MAST_{50}$, (below -3° C), except for the far western (i.e. more maritime) Asik station with $MAST_{50}$ of -2.4° C. Most BELA and CAKR stations were warmer (MAAT -2° C to -4° C), but with MAST still well below freezing ($MAST_{50}$ of -1.5° C to -3.4° C), except for Serpentine Hot Springs, which was close to 0° C. The Kavet Creek station in KOVA was exceptionally warm, with MAAT of -2.4° C and $MAST_{50}$ of +1.6° C, i.e. too warm to support permafrost under current conditions. This station has 1 m-tall shrubs and scattered trees, regenerating from a fire of uncertain date. Our soil temperature record there has just begun, but judging from the difference $MAST_{50}$-MAAT of about +4° C and MAAT colder than -4° C for most of 2009-2014, the MAST was probably sub-freezing, and thus permafrost was stable at Kavet Creek until quite recently.

The recent observed MAAT at the climate stations are higher than the modeled values by PRISM Climate Group (2009; Fig. 3 and Table 6). This reflects the recent warm spell more than modeling error: for example, the long-term normal MAAT for the period 1971-2000 (NCDC 2002) for Bettles and Kotzebue are -5.1° C and -5.7° C, quite close to the PRISM modeled values of -5.4° C for both stations (Table 6). The median difference between recent observed and modeled MAAT at our climate stations, an estimate of the magnitude of recent warming above the long-term average, is about +2° C. The southern portions of KOVA and GAAR have long-term MAAT in the -4° to -6° C range, and significant areas of forest and tall shrub vegetation with deep snowpacks and probably large MAST-MAAT differences due to snow (e.g. as high as 4° C based on our data at Kavet Creek). If recent warm temperatures were to persist, These areas would warm by about +2° C to reach MAAT of -2° to -4° C, and the likely result would be permafrost degradation on relatively warm sites: those with MAST-MAAT greater than 2° C. Most lowland tundra areas in western ARCN, with MAAT of -5 to -6° C (yellow in Fig. 2), would warm to MAAT -3 to -4° C, but given their typical MAAT-MAST differences of 3° C or less, permafrost should remain largely stable, albeit with some increase in active layer thickness and little margin available for additional warming.

The scenario described above for permafrost thaw with warming follows that predicted by modeling of ground temperatures using projections of temperature increase from global circulation models by Panda et al. (2016, in preparation).They predict that with projected warming of about 2° C by mid-century, permafrost would remain stable over most of ARCN, except the southern interior portions of KOVA and GAAR. An additional 2° C of warming in the latter half of the century would destabilize large areas of permafrost in the lowland and western portions of ARCN, including most of the region colored yellow or brown in Fig. 2 with current MAAT warmer than -6° C.

Table 6. Mean Annual Air Temperatures and Soil Temperatures, 2013-2015

NPS Unit	Station	MAAT Modeled[1] ° C	MAAT[2] Recent ° C	$MAST_{50}$ $(MAST_{75})^2$ Recent ° C
Non-NPS	Bettles NWS	-5.4	-3.7	ND
Non-NPS	Kotzebue NWS	-5.4	-2.4	ND
Non-NPS	Chandalar Shelf	-8.2	ND	ND
Non-NPS	Coldfoot	-5.5	ND	ND
Non-NPS	Galbraith Lake	-9.4	ND	ND
Non-NPS	Kotzebue (borehole)	-5.4	ND	ND
BELA	Devil Mtn	-5.4	-3.8	-3.0
BELA	Ella Creek	-5.8	-4.0	-2.3
BELA	HooDoo Hills	-5.5	-3.8	-3.4
BELA	Midnight Mountain	-5.8	ND	ND
BELA	Serpentine Hot Springs	-5.1	-2.8	+0.1
CAKR	Mt Noak	-5.2	-2.1	-1.5 (-1.5)
CAKR	Tahinichok	-5.7	-3.1	-3.1 (-2.8)
GAAR	Chimney Lake	-6.5	-4.5	-3.2 (-3.5)
GAAR	Killik Pass	-8.3	-7.0	-4.2
GAAR	Pamichtuk Lake	-5.8	-4.8	-5.0
GAAR	Ram Creek	-6.6	-5.2	-4.2
KOVA	Kavet Creek	-4.9	-2.4	+1.6
KOVA	Salmon River	-7.2	ND	ND
NOAT	Asik	-5.6	-2.3	-2.4
NOAT	Howard Pass	-10.2	-6.0	-6.1
NOAT	Imelyak	-5.1	-4.8	-3.9
NOAT	Kaluich	-5.7	-5.7	-3.2
NOAT	Kelly SNOTEL	-5.9	-2.3	ND
NOAT	Noatak RAWS	-8.6	-6.3	ND
NOAT	Sisiak	-9.7	-4.6	-3.9 (-4.0)

[1]Modeling by PRISM Climate Group (2009), for the period 1971-2000.

[2]Mean of all available running 12-month means since April 2013, when the recent spell of relatively constant warm temperatures began (see Figs. 5-8)

Thaw Degree-Days

The sum of thaw degree-days (TDD) provides an index of the summer warmth available for active-layer thaw. A long-term perspective is provided by the sum of TDD at Bettles and Kotzebue (Fig. 12). The climatic shift in 1976-77 is apparent on these data sets: warm summers at Bettles had over 1600 TDD through 1976 and over 1800 TDD after 1976, while at Kotzebue warm summers had over 1200 TDD through 1976 and about 1400 after. The unusually warm summer of 2005 at Kotzebue is apparent, with its record sum of TDD of 1570° C-days. That summer triggered numerous active-layer detachments (small landslides due to permafrost thaw) in the study area (Swanson 2014, Balser 2015). Note that Figs. 12 and 13 include 2015, while the NPS data presented here do not. The Kotzebue data rose from a relative low of 1100° C in 2012 to a relatively high value 1380° C in 2014. Summer warmth during this period at Bettles, Kavet Creek and Noatak RAWS was not exceptional (Figs. 12 and 13).

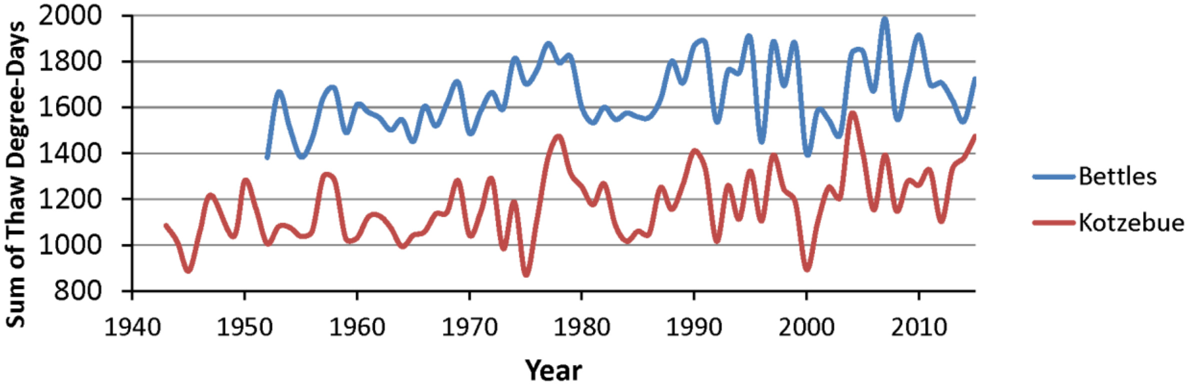


Figure 12. Long-term record of sum of air thaw degree-days (air temperature) at Bettles and Kotzebue.

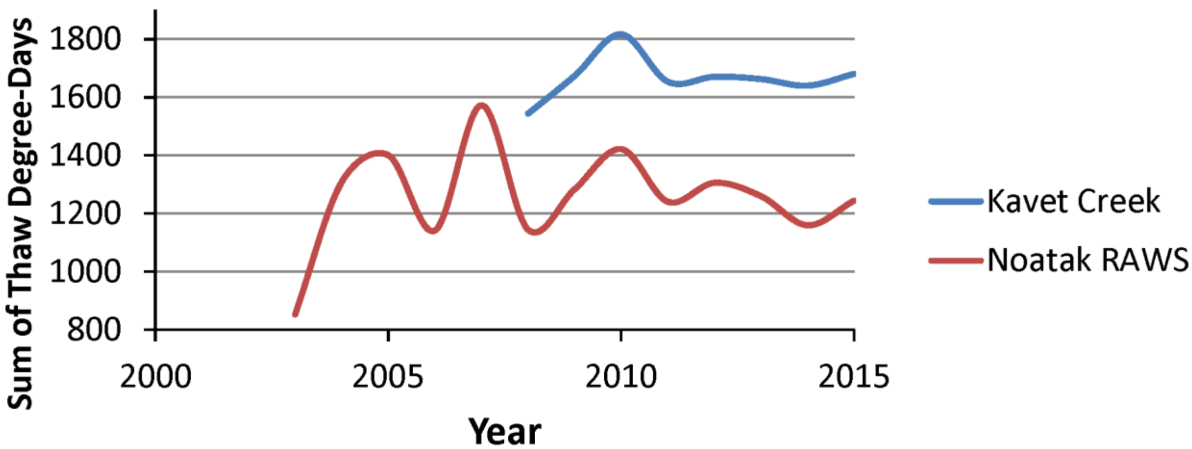


Figure 13. Sum of air thaw degree-days at Kavet Creek and Noatak RAWS.

The sum of TDD for the air and 10 cm depth in the soil at the ARCN monitoring stations for our short period of record are presented in Table 7. Both of these measures may be useful indicators of active-layer layer dynamics in the future. The sum of TDD at 10 cm in the soil is typically lower than the sum of TDD in the air, especially where an organic surface layer strongly damps the surface temperature signal (e.g., Devil Mountain in BELA and Kelly SNOTEL in NOAT). In the western part of ARCN (BELA, CAKR, and the two westernmost NOAT stations), TDD generally increased from 2012 to 2014 in parallel with Kotzebue. In eastern NOAT and GAAR (and Bettles, Fig. 12), the sum of TDD in 2014 was actually lower than in 2013, a trend opposite from MAST and MAAT. This occurs when a cool summer is combined with a mild winter.

Table 7. Sum of thaw degree-days in air in soil (10 cm depth)

NPS Unit	Station	Sum of Thaw Degree-Days, °C-day Air/Soil 10 cm		
		2012	**2013**	**2014**
BELA	Devil Mtn	845/470	1018/562	995/538
BELA	Ella Creek	ND	865/898	844/814
BELA	Serpentine	1032/ND	1213/1056	1220/1079
CAKR	Mt Noak	1144/792	1217/767	1223/840
CAKR	Tahinichok	1077/ND	1101/ND	1101/1091
GAAR	Chimney Lake	ND	1025/ND	823/ND
GAAR	Killik Pass	ND	726/517	571/466
GAAR	Pamichtuk Lake	ND	ND	928/848
GAAR	Ram Creek	ND	ND	ND
NOAT	Asik	ND	1166/1003	1180/1022
NOAT	Howard Pass	ND	989/894	823/753
NOAT	Imelyak	ND	796/ND	731/824
NOAT	Kaluich	ND	942/629	853/631
NOAT	Kelly SNOTEL	1374/ND	1353/477	1398/456
NOAT	Sisiak	1069/ND	1041/814	982/772

Deep Borehole Temperatures

The four deep boreholes in the vicinity of ARCN show generally increasing permafrost temperatures through the period of record, from 1985 to 2015 (Fig. 14). The temperature increase appears to have leveled off in the past 5 to 10 years at all locations except Galbraith Lake. The total increase since the late 1980s ranges from about 0.8° C at Galbraith Lake and Chandalar Shelf to about 0.3° C at Kotzebue. The strong damping effect of the ground on surface temperature fluctuations nearly eliminates the effect of short-term (less than 5 year) temperature cycles from these deep (26 m) measurements, and the post-2012 warming has not yet shown its effects. Additional warming of 2° C (approximately the amount of recent warming in MAAT, were it not to be balanced by a future cold cycle) would destabilize permafrost at Coldfoot and Chandalar Shelf. Analysis of these borehole temperatures, along with others in the statewide network, by Romanovsky et al. (2015) shows that permafrost temperatures have generally increased everywhere since the 1980s, with the greatest increases near the arctic coast and flat trends in recent years in interior locations. Much of the rise is apparently due to increased snow cover (Steiglitz 2003), since long-term mean temperatures have generally not risen during this period at most locations except the arctic coast (Wendler et al. 2012, 2014).

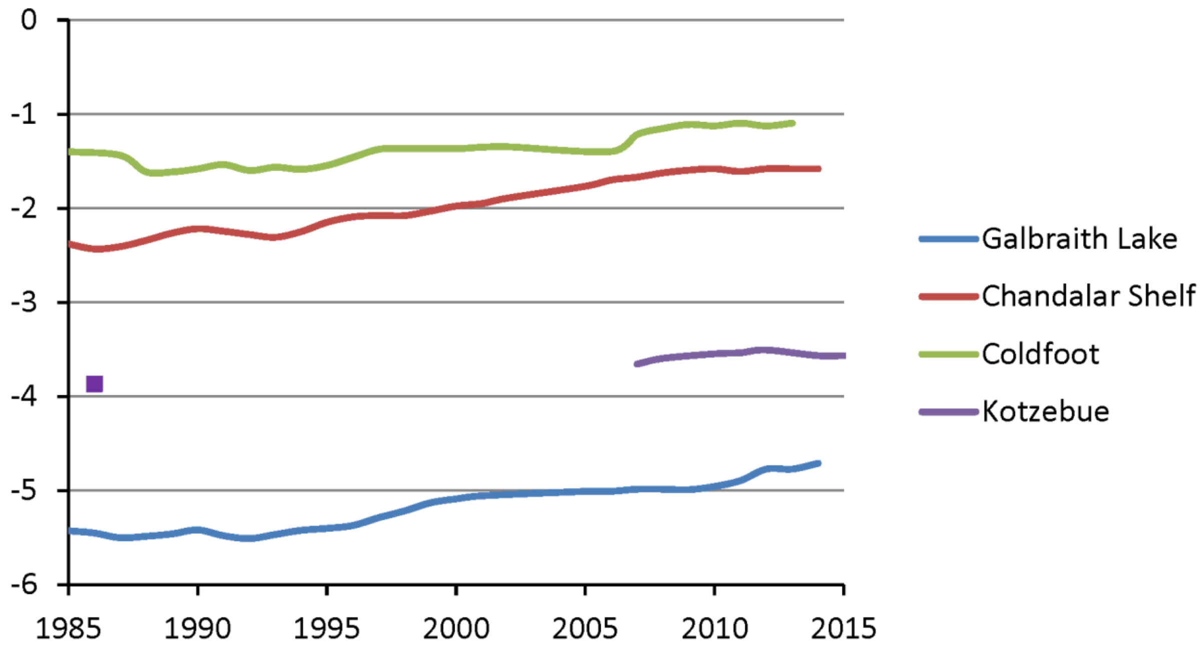


Figure 14. Time series of permafrost temperatures a 26 m depth at 4 borehole monitoring stations in the vicinity of ARCN. The depth of 26 m was chosen because it is just below the depth of detectable annual variation (about 20 m; Osterkamp 2005) and it was available for all sample years at all four sites. Data provided courtesy of Vladimir Romanovsky, University of Alaska Fairbanks.

Literature Cited

Balser, A. W. 2015. "Retrogressive Thaw Slumps and Active Layer Detachment Slides in the Brooks Range and Foothills of Northern Alaska: Terrain and Timing." Ph.D. Dissertation, Fairbanks, Alaska: Alaska. http://www.researchgate.net/profile/Andrew_Balser/publication/274710153_Retrogressive_Thaw_Slumps_and_Active_Layer_Detachment_Slides_in_the_Brooks_Range_and_Foothills_of_Northern_Alaska_Terrain_and_Timing/links/5526c4800cf229e6d635db34.pdf.

Burn, C. R., and C. A. S. Smith. 1988. "Observations of the' Thermal Offset' in near-Surface Mean Annual Ground Temperatures at Several Sites near Mayo, Yukon Territory, Canada." *Arctic*, 99–104.

Hartmann, B., and G. Wendler. 2005. "The Significance of the 1976 Pacific Climate Shift in the Climatology of Alaska." *Journal of Climate* 18 (22): 4824–39.

Hill, K., and P. Sousanes. 2015a. "Climate Station Maintenance in the Arctic Network: 2014 Summary." Natural Resource Data Series NPS/ARCN/NRDS—2015/744. Fort Collins, Colorado: National Park Service. https://irma.nps.gov/App/Reference/Profile/2218928.

———. 2015b. “Climate Station Maintenance in the Arctic Network: 2015 Summary.” Natural Resource Data Series NPS/ARCN/NRDS—2015/XXX. Fort Collins, Colorado: National Park Service.

Hinkel, K. M., and J. R. Nicholas. 1995. “Active Layer Thaw Rate at a Boreal Forest Site in Central Alaska, USA.” *Arctic and Alpine Research* 27 (1): 72–80.

Hirsch, R. M., J. R. Slack, and R. A. Smith. 1982. “Techniques of Trend Analysis for Monthly Water Quality Data.” *Water Resources Research* 18 (1): 107–21.

Hisch, R. M., and J. R. Slack. 1984. “A Nonparametric Trend Test for Seasonal Data with Serial Dependence.” *Water Resources Research* 20 (6). https://profile.usgs.gov/myscience/upload_folder/ci2012Oct1508284428033A%20Nonparametric%20Trend%20Test%20for%20Seasonal%20Data%20With%20Serial%20Dependence.pdf.

Jorgenson, M. T., C. H. Racine, J. C. Walters, and T. E. Osterkamp. 2001. “Permafrost Degradation and Ecological Changes Associated with a Warming Climate in Central Alaska.” *Climatic Change* 48 (4): 551–79.

Jorgenson, M. T., J. E. Roth, P. F. Miller, M. J. Macander, M. S. Duffy, A. F. Wells, G. V. Frost, and E. R. Pullman. 2009. “An Ecological Land Survey and Landcover Map of the Arctic Network.” ARCN/NRTR-2009/270. Fort Collins (CO): National Park Service. https://irma.nps.gov/App/Reference/Profile/663934.

Jorgenson, M. T., Y. L. Shur, and E. R. Pullman. 2006. “Abrupt Increase in Permafrost Degradation in Arctic Alaska.” *Geophysical Research Letters* 33 (2). http://onlinelibrary.wiley.com/doi/10.1029/2005GL024960/pdf.

Jorgenson, M. T., K. Yoshikawa, M. Kanevskiy, Y. Shur, V. Romanovsky, S. Marchenko, G. Grosse, J. Brown, and B. Jones. 2008. *Permafrost Characteristics of Alaska*. Institute of Northern Engineering, University of Alaska Fairbanks. http://www.cryosphericconnection.org/resources/alaska_permafrost_map_dec2008.pdf.

Lawler, J. P., S. D. Miller, D. Sanzone, J. Ver Hoef, and S. B. Young. 2009. “Arctic Network Vital Signs Monitoring Plan.” Natural Resource Report NPS/ARCN/NRR-2009/088. Fort Collins, Colorado: National Park Service.

Marchetto, A. 2015. *Rkt: Mann-Kendall Test, Seasonal and Regional Kendall Tests. R Package Version 1.4*. http://CRAN.R-project.org/package=rkt.

NCDC. 2002. “Climatography of the United States No. 81. Monthly Station Normals of Temperature, Precipitation, and Heating and Cooling Degree Days, 1971-2000.” Asheville, North Carolina: National Climatic Data Center/NESDIS/NOAA.

Nelson, F. E., N. I. Shiklomanov, G. R. Mueller, K. M. Hinkel, D. A. Walker, and J. G. Bockheim. 1997. “Estimating Active-Layer Thickness over a Large Region: Kuparuk River Basin, Alaska, USA.” *Arctic and Alpine Research* 29 (4): 367–78.

NOAA. 2015. “Data Tools: 1981-2010 Normals.” National Centers for Environmental Information, National Oceanic and Atmospheric Administration. http://www.ncdc.noaa.gov/cdo-web/datatools/normal.

Osterkamp, T. E. 2003. “Establishing Long-Term Permafrost Observatories for Active-Layer and Permafrost Investigations in Alaska: 1977–2002.” *Permafrost and Periglacial Processes* 14 (4): 331–42.

———. 2005. “The Recent Warming of Permafrost in Alaska.” *Global and Planetary Change* 49 (3): 187–202.

———. 2007. “Characteristics of the Recent Warming of Permafrost in Alaska.” *Journal of Geophysical Research: Earth Surface (2003–2012)* 112 (F2): F02S02. doi:10.1029/2006JF000578.

Osterkamp, T. E., and V. E. Romanovsky. 1996. “Characteristics of Changing Permafrost Temperatures in the Alaskan Arctic, USA.” *Arctic and Alpine Research*, 28 (3): 267–73.

Panda, S. K., S. S. Marchenko, and V. E. Romanovsky. 2016. “High-Resolution Permafrost Modeling in the Arctic Network of National Parks, Alaska.” Natural Resource Report NPS/ARCN/NRR-2016/XXX. Fort Collins, Colorado: National Park Service.

PRISM Climate Group. 2009. “July Mean Average Temperature for Alaska 1971-2000; Annual Mean Average Temperature for Alaska 1971-2000. Corvallis (OR): Oregon State University.” http://prism.oregonstate.edu.

R Core Team. 2014. “R: A Language and Environment for Statistical Computing.” Vienna, Austria: R Foundation for Statistical Computing. http://www.R-project.org.

Romanovsky, V. E., and W. Cable. 2014. “Establishing a Distributed Permafrost Observation Network in Western Alaska.” Western Alaska Landscape Conservation Cooperative Project 2014 Final Performance Report. Fairbanks, Alaska: Western Alaska LCC.

Romanovsky, V. E., S. L. Smith, H. H. Christiansen, N. I. Shiklomanov, D. A. Streletskiy, D. S. Drozdov, G. V. Malkova, N. G. Oberman, A. L. Kholodov, and S. S. Marchenko. 2015. “[Global Climate] Terrestrial Permafrost [in ‘State of the Climate in 2014’].” *Bulletin of the American Meteorological Society* 96 (7): ES1–32. doi:10.1175/2015BAMSStateoftheClimate.1.

Schoeneberger, P. J., D. A. Wysocki, and E. C. Benham. 2012. “Soil Survey Staff. 2012. Field Book for Describing and Sampling Soils, Version 3.0.” Lincoln (NE): Natural Resources Conservation Service, National Soil Survey Center. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_052523.pdf.

Soil Survey Division Staff. 1993. *Soil Survey Manual. U.S. Department of Agriculture Handbook 18*. Washington (DC): Soil Conservation Service.

Soil Survey Staff. 2014. *Keys to Soil Taxonomy, 12th Ed.* 12th ed. Washington, DC: USDA-Natural Resources Conservation Service. http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/class/?cid=nrcs142p2_053580.

Stieglitz, M., S. J. Déry, V. E. Romanovsky, and T. E. Osterkamp. 2003. "The Role of Snow Cover in the Warming of Arctic Permafrost." *Geophysical Research Letters* 30 (13). http://onlinelibrary.wiley.com/doi/10.1029/2003GL017337/full.

Sturm, M., J. Holmgren, and G. E. Liston. 1995. "A Seasonal Snow Cover Classification System for Local to Global Applications." *Journal of Climate* 8 (5): 1261–83.

Swanson, D. K. 2013. "Monitoring of Retrogressive Thaw Slumps in the Arctic Network, 2012." Natural Resource Data Series NPS/ARCN/NRDS—2013/591. Fort Collins, Colorado: National Park Service.

———. 2014. "Mapping of Erosion Features Related to Thaw of Permafrost in the NPS Arctic Inventory and Monitoring Network, Alaska." Natural Resource Technical Report NPS/ARCN/NRTR—2014/912. Fort Collins (CO): National Park Service. https://irma.nps.gov/App/Reference/Profile/2216465.

U.S. Army Corps of Engineers. 1950. "Investigation of Military Construction in Arctic and Subarctic Regions 1945-1948." St. Paul, MN: U. S. Army Corps of Engineers, St. Paul District. http://oai.dtic.mil/oai/oai?verb=getRecord&metadataPrefix=html&identifier=AD0703360.

Van Oldenborgh, G. J., M. Collins, J. Arblaster, J. H. Christensen, J. Marotzke, S. B. Power, M. Rummukainen, and T. Zhou. 2013. "Annex I: Atlas of Global and Regional Climate Projections." In *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker, D. Qin, Plattner G.-K., Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, and Midgley P M, 1311–93. Cambridge, United Kingdom and New York, (NY): Cambridge University Press.

Wendler, G., L. Chen, and B. Moore. 2012. "The First Decade of the New Century: A Cooling Trend for Most of Alaska." *Open Atmospheric Science Journal* 6: 111–16.

Wendler, G., B. Moore, and K. Galloway. 2014. "Strong Temperature Increase and Shrinking Sea Ice in Arctic Alaska." *The Open Atmospheric Science Journal* 8: 7–15.

Appendix: Soil and Site Descriptions

Howard Pass Climate Station

Clasification: Typic Gelorthent
Vegetation: barren with small patches of Dryas. Species cover: Dryas octopetala 5%, Salix phlebophylla 1%; <1% of: Flavocetraria nivalis, Minuartia sp., Oxytropis sp., Pedicularis sp., Potentilla uniflora, Thamnolia subuliformis
Parent material: Felsic volcanic rock
Landform: Mountain
Microfeature: Sorted circles
Elevation: 2062 ft (628 m)
Slope gradient: 0 percent
Slope Aspect: N/A
Slope shape: convex
Hillslope position: Summit
Drainage: Well drained
Described by: David Swanson, 20 July 2015

A - 0 to 8 cm; black (10YR 2/1) extremely cobbly sandy loam; weak medium granular structure; friable; common very fine and fine roots; 20 percent pebbles, 50 percent cobbles, and 5 percent stones; slightly acid (pH 6.2); clear wavy boundary.

BC - 8 to 35 cm; dark yellowish brown (10YR 3/4) extremely cobbly sandy loam; weak medium granular structure; friable; few very fine roots; 20 percent pebbles, 50 percent cobbles, and 5 percent stones; moderately acid (pH 5.8).

Notes: Sorted circles form a network, circle diameters are 1-2 m. No water or frozen soil was observed.
Classification notes: permafrost is clearly present here, with a mean annual soil temperatures (MAST) at all depths of about -5.5° C in the past year. But even at 50 cm depth the summer soil temperatures are +6° to +10° C, which suggests a very deep active layer (>2 m) and thus a non-Gelisol classification.

Imelyak climate station

Classification: Typic Gelorthent
Vegetation: barren with small patches of Dryas, Salix, and grass. Species cover: Dryas octopetala 3%, Hierchloe alpine 3%, Salix phlebophylla 3%, unknown mosses 3%, Oxytropis kokrinensis 1%; <1% of: Cassiope tetragona, Luzula sp., Pedicularis sp., Thamnolia subuliformis.
Parent material: Argillite and meta-graywacke
Landform: Mountain
Microfeature: Nonsorted circles, earth hummocks in some concavities
Elevation: 3569 ft (1096 m)
Slope gradient: 0 percent

Slope aspect: N/A
Slope shape: convex
Hillslope position: Summit
Drainage: Well drained
Described by: David Swanson, 21 July 2015

AB - 0 to 3 cm; very dark grayish brown (10YR 3/2) very gravelly sandy loam; weak medium granular structure; friable; common very fine to medium roots; 50 percent pebbles and 5 percent cobbles; moderately acid (pH 5.6); clear wavy boundary.

Bw - 3 to 12 cm; dark brown (10 YR 3/3) weak medium granular structure; friable; common very fine to medium roots; 40 percent pebbles and 5 percent cobbles; moderately acid (pH 5.6); clear wavy boundary.

Cr - 12 to 40 cm; brown (10YR 4/3) gravel; structureless; loose; 98 percent pebbles; moderately acid (pH 6.0).

Notes: No water or frozen soil was observed.
Classification notes: Permafrost is clearly present here, as shown by MASTs during the past year at 20 and 50 cm of -3.2° and -3.4° C. Summer soil temperatures at 50 cm depth were 6° to 9° C, which suggests an active layer more than 2 m thick, hence a non-Gelisol. The Bw horizon is very weak and too thin (<15 cm) to be a cambic horizon, hence the Gelorthent classification.

Kaluich Climate Station

Classification: Typic Gelorthent
Vegetation: Dryas tundra. Species cover: Dryas octopetala 40%, Vaccinium uliginosum 3%; <1% of: Anenome sp., Armeria maritima, Artemisia c.f. furcata, Asahinea sp., Campanula c.f. aurita, Carex scripoidea, Cassiope tetragona, Castilleja elegans, Diapensia lapponica, Flavocetraria cucullata, Geum glaciale, Oxytropis kokrinensis, Oxytropis sp., Pedicularis sp., Rhododentron lapponicum, Salix arctica, Salix reticulata, Saxifraga flagellaris, Thamnolia subuliformis, Vulpicida tilesii.
Parent material: Colluvium from argillite and sandstone, over residuum from argillite
Landform: Mountain
Microfeature: Earth hummocks, weak non-sorted circles
Elevation: 2486 ft (758 m)
Slope gradient: 2 percent
Slope Aspect: South
Slope shape: convex
Hillslope position: Summit
Drainage: Well drained
Described by: David Swanson, 21 July 2015

A - 0 to 6 cm; black (10YR 2/1) gravelly loam; weak fine granular structure; friable; common very fine and fine roots; 20 percent pebbles and 5 percent cobbles; neutral (pH 6.6); clear wavy boundary.

AB - 6 to 24 cm; black (5Y 2.5/1) gravelly sandy loam; structureless; friable; few fine roots; 20 percent pebbles, 10 percent cobbles, and 10 percent stones; neutral (pH 6.8); abrupt broken boundary.

Cr - 25 to 45 cm; black (N 2.5/) cobbles; structureless; loose; carbonate pendants on undersides of cobbles; 30 percent pebbles and 60 percent cobbles; slightly alkaline (pH 7.6).

Notes: The dark soil color is inherited from the parent material. The A and AB horizons have variable thickness and are discontinuous due to cryoturbation, the depths given are averages. The upper two horizons are colluvium and include some sandstone cobbles from an exposure about 100 m upslope. No water, saturated soil, or frozen soil was encountered.

Classification notes: the soil is cryoturbated and thus classifies as a Gelisol if permafrost occurs above 2 m depth. Soil temperatures at 50 cm depth in the past year averaged -3.5° C and in late summer were around 6° C, so there is definitely permafrost at some depth, but I estimate permafrost to be a little deeper than 2 m depth here, hence the Orthent classification. If it is shallower, the soil classifies as Lithic Haploturbel (if true bedrock is above 50 cm depths), or Typic Haploturbel (if bedrock is below 50 cm depth).

Kavet Creek RAWS

Classification: Turbic Haplogelept

Vegetation: Closed low scrub, shrub birch. Species cover: Equisetum arvense 80%, Betula nana 70%, Vaccinium uliginosum 25%, Ledum palustre 5%, Picea glauca 3%, 1% of: Salix glauca, Betula neoalaskana, Betula nana-B. neoalaskana hybrid, Polytrichum sp.

Parent material: Loess

Landform: Loess plain

Microfeature: None

Elevation: 235 ft (72 m)

Slope gradient: 3%

Slope Aspect: northeast (45°)

Slope shape: slightly convex downslope, linear across the slope

Hillslope position: N/A

Drainage: Somewhat poorly drained

Described by: David Swanson, 22 July 2015

Oi - 0 to 2 cm; black (10YR 2/1) peat; slightly acid (pH 6.4); abrupt smooth boundary.

A - 2 to 6 cm; very dark brown (10YR 2/2) silt loam; structureless; friable; moderately acid (pH 5.6); many very fine to medium roots; abrupt broken boundary.

Bw - 6 to 12 cm; dark brown (7.5 YR 3/3) silt loam; friable; moderately acid (pH 5.8); few very fine and fine roots; abrupt broken boundary.

Bg - 12 to 105 cm; gray (2.5Y 5/1) silt loam; friable; neutral (pH 7.0); few very fine and fine roots.

Notes: The A and Bw horizons have variable thickness and A material was buried in the Bw and Bg due to cryoturbation. The strong cryoturbation and gley colors are probably relict from times in the past when the soil had permafrost closer to the surface and a thicker surface organic horizon. The site has post-fire seral vegetation and the soil has a thick active layer due to post-fire soil warming. The drainage class is difficult to determine because of relict redox features and may in fact be currently "moderately well drained". No water or frozen soil were encountered to a depth of 105 cm. Classification notes: this soil is cryoturbated and thus would classify as a Gelisol if permafrost were above 2 m depth, probably an Aquic Haploturbel. The soil was probably a Typic Aquiturbel in the past under late seral vegetation. We have one year of soil temperature data that show a MAST at 10 and 20 cm of +1.7° and +1.5° C, due to post-fire soil warming and mild temperatures during the last two years. Briefly last August when we had 50 cm soil temperatures they were about 5° C, and chances are good that permafrost has receded below 2 m depth. If so, the soil is in the Gelept suborder, though below that gets tricky due to uncertainty about the water regime. Redox features are adequate for an Aquic Great Group or Subgroup, the water regime is uncertain; it has certainly been Aquic in the past and aquic conditions are probably present briefly for some period in the spring. The current rather dry soil conditions and strong cryoturbation make Turbic Haplogelept most descriptive, but one could make a case for Aquic Haplogelept or Turbic Gelaquept also. If warm temperatures persist, the soil could become a Aquic Haplocryept.

Noatak RAWS

Classification: Typic Aquiturbel
Vegetation: Open low scrub, mixed shrub-sedge tussock tundra. Species cover: Ledum palustre 15%, Betula nana 10%, Carex bigelowii 5%, Salix glauca 3%, 1% of: Aulocomnium plaustre, Eriophorum vaginatum, Salix pulchra, Vaccinium uligonosum, Vaccinium vitis-idaea; <1% of: Bistorta plumosa, Empetrum hermaphroditum, Hierchloe alpine, Oxytropis maydelliana.
Parent material: Glacial till
Landform: Glacial till plain
Microfeature: Earth hummocks and tussocks
Elevation: 985 ft (300 m)
Slope gradient: 0%
Slope aspect: N/A
Slope shape: Flat
Hillslope position: N/A
Drainage: Poorly drained
Described by: David Swanson, 21 July 2015

Oi1 - 0 to 7 cm; dark brown (7.5YR 3/3) peat; few very fine and fine roots; moderately acid (pH 5.6); abrupt wavy boundary.

Oi2 - 7 to 10 cm; black (10YR 2/1) peat; many very fine to medium roots; moderately acid (pH 5.8); abrupt wavy boundary.

Bg - 10 to 50 cm; dark grayish brown (2.5Y 4/2) and dark gray (2.5 Y 4/1) very gravelly sandy clay loam; structureless; firm; few very fine and fine roots; 40 percent pebbles; slightly acid (pH 6.4).

Notes: Water at 10 cm depth. Probing with shovel reached frozen soil at 68 cm. Hamilton (2010) shows this location as a moraine ridge near to glaciolacustrine deposits, so either parent material is probably possible, though the coarseness suggest till. Some of the pebbles are rounded.
Classification notes: Turbic suborder inferred from the microtopography, texture, and wetness.

Salmon River climate station

Classification: Typic Gelorthent
Vegetation: Barren with patches of low shrub (Betula nana). Species cover: Betula nana 10%, Dryas octopetala 3%, Loiseleura procumbens 1%, Salix phlebophylla 1%, Vaccinium uliginosum 1%; <1% of: Antennaria sp., Carex sp., Cladonia arbuscula/mitis, Cladonia rangiferina/stygia, Flavocetraria nivalis, Hierchloe alpina, Minuartia sp., Oxytropis sp., Stereocaulon sp.
Parent material: Residuum from schist bedrock
Lanform: Mountain ridge, nose
Microfeature: None
Elevation: 1201 ft (366 m)
Slope gradient: 2%
Slope aspect: South
Slope shape: Convex
Hillslope position: Summit
Drainage: Well drained
Described by: David Swanson, 21 July 2015

AC - 0 to 8 cm; black (2.5Y 3/1) very channery silt loam; weak fine granular structure; friable; few very fine and fine roots; 45 percent channers and 5 percent flagstones; moderately acid (pH 6.0); clear smooth boundary.

Cr - 8 to 30 cm; bery dark grayish brown extremely channery sandy loam; structureless; loose; few very fine roots; 75 percent channers and 5 percent flagstones; slightly acid (pH 6.2); abrupt wavy boundary.

R - 30 cm; schist bedrock.

Notes: Channer lag on surface. The R horizon could be a large stone, but true bedrock is close to the surface.
Classification notes: one year of climate records suggest a MAST near 0° C and reaching above 10° C at 50 cm depth. Thus permafrost is very unlikely within 2 m and may not be present at all. If permafrost is absent, the classification is Lithic Cryorthent.

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